PATENT APPLICATION

OPTICAL SPECTRAL POWER MONITORS EMPLOYING FREQUENCY-DIVISION-MULTIPLEXING DETECTION SCHEMES

INVENTORS
Pavel G. Polynkin and Jeffrey P. Wilde

FIELD OF THE INVENTION

[0001]   This invention relates generally to optical spectral monitors and analyzers. More specifically, it relates to a new class of optical spectral power monitors employing novel frequency-division-multiplexing detection schemes, which are well suited for WDM optical networking applications.

BACKGROUND

[0002]   As optical communication networks employing wavelength division multiplexing (WDM) become increasingly pervasive, a new line of optical performance monitors, including spectral power monitors, is in demand.

[0003]   Conventional optical spectral power monitors typically use a wavelength-dispersing means, such as a diffraction grating or a dispersing prism, to separate a multi-wavelength optical signal into a spatial array of spectral channels with distinct center wavelengths. An array of photo-detectors (e.g., photodiodes) is positioned to detect the spectral channels individually, thereby providing an optical power spectrum of the multi-wavelength optical signal. Alternatively, a rotating diffraction grating and a stationary photo-detector, or a movable photo-detector and a stationary diffraction grating, are used to scan the spectral channels sequentially. These prior spectral power monitors are typically high in cost, cumbersome in size and operation, and in some instances require considerable maintenance, rendering them unsuitable for optical networking applications.

[0004]   U.S. Patent No. 5,631,735 of Nagai discloses a spectrometer that uses a diffraction grating for separating an incident light signal into respective wavelength components, impinging onto an array of optical shutter elements. The respective wavelength components are modulated with different frequencies, and subsequently multiplexed to one

5   beam to be detected by a detector. The output signal of the detector is then demodulated in order to derive the intensity of the respective wavelength components.

[0005]   It is known in the art that the diffraction efficiency of a diffraction grating is characteristically polarization sensitive, and may also be wavelength dependent. However, no effort is made in the aforementioned spectrometer of Nagai to mitigate such effects.

10   Moreover, there may be other systematic effects in a practical system, inflicting additional optical loss to an optical beam. As such, the intensity measurement provided by Nagai's spectrometer is not reflective of the actual optical power level of the respective wavelength components in the input light signal.

[0006]   U.S. Patent No. 6,239,889 of Harley et al. discloses a scheme for optical signal

15   power detection in a WDM system. A unique signature bit pattern is inserted in a digital optical signal, where the power level of the signature bit pattern is adjusted at the launching point to a predetermined ratio with the power level of the optical signal to be detected. At a point of interest, a fraction of the modulated optical signal is tapped off, and subsequently converted into an electrical signal. By extracting the fraction of the signature bit pattern from

20   the electrical signal and measuring its power level, the power level of the optical signal can be determined. Such a scheme can also be extended to a plurality of optical signals multiplexed on an optical fiber, where each optical signal is given a unique signature pattern.

[0007]   The aforementioned method of Harley et al. is limited in its application, in that the signature bit patterns have to be inserted on a network level, before any power detection can

25   be made at the point of interest. Moreover, it requires that the predetermined ratio of the power level of the signature bit pattern to the power level of the optical signal be maintained as the optical signal propagates in the network, which might be a difficult proposition in practice.

[0008]   Therefore, it would be an advance in the art to overcome the shortcomings of the foregoing devices and methods and to provide a new line of optical spectral power monitors that can be deployed anywhere in a WDM network and provide accurate detection of the WDM signals.

SUMMARY OF THE INVENTION

[0009]   The present invention provides a method and apparatus for optical spectral power monitoring by way of a novel frequency-division-multiplexing detection scheme. The optical spectral power monitoring apparatus of the present invention comprises an input port for a multi-wavelength optical signal and an output port; a wavelength-disperser that separates the multi-wavelength optical signal by wavelength into multiple spectral channels having a predetermined relative arrangement; and an array of beam-modulating elements positioned such that each beam-modulating element receives a unique one of the spectral channels. The beam-modulating elements are individually controllable such that the optical power levels of the spectral channels coupled into the output port carry distinct dither modulation signals.

[0010]   In the present invention, a "spectral channel" is characterized by a distinct center wavelength and associated bandwidth, and may carry a unique information signal as in WDM optical networking applications. A "dither modulation signal" refers to any modulation in the optical power level of a spectral channel that is caused by the corresponding beam-modulating element, in contrast with other "intrinsic" modulation signals (e.g., information signals) the input multi-wavelength optical signal may carry. Accordingly, the dither modulation signals are allocated in a spectral range that is sufficiently separated from the frequencies of other "intrinsic" modulation signals the spectral channels may carry.

[0011]   In one embodiment of an optical spectral power monitoring apparatus of the present invention, an array of micromirrors serves as the beam-modulating elements; the output port acts as a spatial filter, such that misalignment in coupling a spectral channel to the output port effectively causes the optical power level of the spectral channel coupled into the output port to change. The micromirrors may be under control of a set of mirror-control

(e.g., voltage) signals, such that at nominal positions the micromirrors reflect the corresponding spectral channels into the output port according to predetermined (e.g., maximum) coupling efficiencies. The micromirrors may be further pivoted about the respective nominal positions by way of alternating (or "dither") components in the corresponding mirror-control signals, whereby the optical power levels of the spectral channels coupled into the output port undergo distinct oscillations, hence the dither modulation signals. As such, the micromirrors thus described, along with the output port, effectively function as "spatial light modulators." The micromirrors may be provided by silicon micromachined mirrors that are each pivotable about at least one axis, for example. The output port may be a fiber collimator, an aperture, or other spatial filtering means known in the art.

[0012]   Furthermore, an optical detector may be optically coupled to the output port, so as to convert the received optical power levels to a consolidated electrical signal, which carries the same characteristic dither modulation signals. A synchronous detection unit, in communication with the optical detector, may be used to detect the individual dither modulation signals in the consolidated electrical signal. The characteristics of the dither modulation signals thus detected, along with a predetermined calibration table that takes into account any systematic effect on a channel-by-channel basis, provide an optical power spectrum (i.e., optical power level as a function of wavelength) of the input multi-wavelength optical signal.

[0013]   The aforementioned embodiment may further employ a polarization diversity scheme, so as to mitigate any polarization-dependent effect the constituent optical elements may possess. In this case, a polarization-separating element and a polarization-rotating element may be disposed along the optical path between the input port and the wavelength-disperser, serving to decompose the input multi-wavelength optical signal into first and second polarization components and subsequently rotating the polarization of the second polarization component by 90-degrees. The wavelength-disperser separates the incident optical signals by wavelength into first and second sets of optical beams, respectively. A beam-focuser (e.g., a focusing lens) may focus the first and second sets of optical beams into

corresponding focused spots, impinging onto the micromirrors. Upon being reflected by the respective micromirrors and further multiplexed by the wavelength disperser, the reflected first and second sets of optical beams may be re-combined by way of a polarization-combining element in conjunction with an auxiliary polarization-rotating element, prior to

5   being coupled into the output port.

[0014]   The reflected first and second sets of optical beams may alternatively be coupled into the output port and an auxiliary output port, whereby the optical power levels coupled into each output port carry distinct dither modulation signals. First and second optical detectors may be optically coupled to the output port and the auxiliary output port,

10   respectively. First and second synchronous detection units may be in communication with the first and second optical detectors and serve to detect the dither modulation signals associated with the first and second sets of optical beams, respectively. The characteristics of the dither modulation signals thus detected, combined with predetermined calibration tables, enable an optical power spectrum associated with each polarization component in the input

15   multi-wavelength optical signal to be separately determined.

[0015]   In another embodiment of the present invention, the beam-modulating elements are provided by an array of spatial light modulators known in the art, such as electro-optic intensity modulators, in a polarization diversity scheme. In this case, the first and second sets of optical beams dispersed by the wavelength-disperser impinge onto the corresponding

20   electro-optic modulating elements, followed by a beam-reflector (e.g., a mirror). The electro-optic modulating elements may operate under control of a set of distinct alternating (or dither) control signals, so as to introduce dither modulation signals in the optical power levels of the optical beams. As such, upon a round-trip through the respective electro-optic modulating elements by way of the beam-reflector and further multiplexed by the

25   wavelength-disperser, the first and second sets of optical beams may be directed into first and second optical detectors, respectively, whereby the optical power levels received by each optical detector carry distinct dither modulation signals. First and second synchronous detection units may be in communication with the first and second optical detectors and serve to detect the dither modulation signals associated with the first and second sets of optical

beams, respectively. The characteristics of the dither modulation signals thus detected, combined with predetermined calibration tables, enable an optical power spectrum associated with each polarization component in the input multi-wavelength optical signal to be separately determined.

5   [0016]   In the present invention, the wavelength-disperser may generally be a ruled diffraction grating, a holographic grating, an echelle grating, a curved diffraction grating, a transmission grating, a dispersing prism, or other types of wavelength-separating means known in the art. The input port may be a fiber collimator. The polarization-separating element may be a polarizing beam splitter, a birefringent beam displacer, or other types of

10   polarization separating means known in the art. The polarization-rotating element may be a half-wave plate, a Faraday rotator, a liquid crystal rotator, or any other polarization-rotating means known in the art that is capable of rotating the polarization of an optical beam by 90-degrees. The polarization-combining element may be a birefringent element, e.g., a birefringent beam displacer operated in reverse. It may also be other means known in the art

15   that is capable of combining two optical beams by way of polarization.

[0017]   The optical spectral power monitoring apparatus of the present invention may further include one or more reference signals and corresponding reference-position-sensing elements, along with one or more appropriate alignment-adjusting elements, for monitoring the alignment between the spectral channels and the respective beam-modulating elements

20   and correcting for shift in the alignment that may arise over the course of operation.

[0018]   As such, the present invention provides an optical apparatus that is capable of introducing distinct dither modulation signals in multiple spectral channels in a frequency-division-multiplexed fashion. The distinct dither modulation signals enable the multiplexed spectral channels to be individually detected (e.g., by way of synchronous detection),

25   whereby an optical power spectrum of the spectral channels can be derived. Such dither modulation signals may also be used as "identification markers" (or frequency tags) for identifying individual spectral channels in an optical networking application.

[0019]   The novel features of this invention, as well as the invention itself, will be best understood from the following drawings and detailed description.

BRIEF DESCRIPTION OF THE FIGURES

[0020]   FIGS. **1A-1B** show a first embodiment of an optical spectral power monitoring apparatus of the present invention, employing an array of micromirrors as the beam-modulating elements and a single output port;

[0021]   FIG. **1C** illustrates an exemplary plot of coupling efficiency as a function of micromirror's pivoting angle and an exemplary plot of micromirror's pivoting angle as a function of mirror-control (voltage) signal;

[0022]   FIG. **2** depicts a second embodiment of an optical spectral power monitoring apparatus of the present invention, employing an array of micromirrors as the beam-modulating elements and a plurality of output ports;

[0023]   FIGS. **3A-3B** show a third embodiment of an optical spectral power monitoring apparatus of the present invention, employing an array of micromirrors as the beam-modulating elements in a polarization diversity scheme;

[0024]   FIG. **3C** shows a fourth embodiment of an optical spectral power monitoring apparatus of the present invention, employing an array of micromirrors as the beam-modulating elements in a polarization diversity scheme;

[0025]   FIGS. **4A-4B** depict a fifth embodiment of an optical spectral power monitoring apparatus of the present invention, employing an array of electro-optic modulating elements in a polarization diversity scheme; and

[0026]   FIG. **5** shows a sixth embodiment of an optical spectral power monitoring apparatus of the present invention, illustrating how to ascertain optimal alignment in the present invention.

DETAILED DESCRIPTION

[0027]   FIG. 1A depicts a first embodiment of an optical spectral power monitoring apparatus according to the present invention. By way of example to illustrate the general principles and the architecture of the present invention, optical spectral power monitoring apparatus **100** comprises a plurality of input and output ports **110**, including an input port **110-1** and an output port **110-2**, which may be in the form of fiber collimators; a wavelength-disperser which in one form may be a diffraction grating **120**; a beam-focuser in the form of a focusing lens **130**; and an array of beam-modulating elements **140** which in one form may comprise micromirrors. The optical spectral power monitoring apparatus **100** may further include an optical detector **150** which in one form may be a photodiode along with associated detection circuit, and a synchronous-detection unit **160**.

[0028]   The principal operation of the optical spectral power monitoring apparatus **100** may be as follows. A multi-wavelength optical signal (e.g., containing wavelengths λ_1 through λ_N) emerges from the input port **110-1**. The diffraction grating **120** angularly separates the incident multi-wavelength optical signal by wavelength into multiple spectral channels having a predetermined relative arrangement. The focusing lens **130** may in turn focus the spectral channels into corresponding focused spots (e.g., in a spatial array with the predetermined relative arrangement). The micromirrors **140** may be positioned such that each micromirror receives a unique one of the spectral channels. The micromirrors **140** are individually controllable and movable (e.g., pivotable or rotatable), such that, upon reflection, the spectral channels are multiplexed by the diffraction grating **120** and directed into the output port **110-2**. The optical detector **150**, optically coupled to the output port **110-2**, converts the received spectral channels into a consolidated electrical (e.g., voltage) signal, which may subsequently be fed to the synchronous-detection unit **160**, as will be discussed in further detail below.

[0029]   In the present invention, a "spectral channel" is characterized by a distinct center wavelength (e.g., λ_i) and associated bandwidth, and may carry a unique information signal as in WDM optical networking applications. For purposes of illustration and clarity, only a selective few (e.g., three) of the spectral channels in the input multi-wavelength optical signal

are graphically illustrated in FIG. 1A (and the following figures). It should be noted, however, that there can be any number of the spectral channels in an optical spectral power monitoring apparatus of the present invention (so long as the number of the spectral channels is commensurate with the number of the beam-modulating elements employed in the system). Moreover, the optical beams representing the spectral channels shown in FIG. 1A and the following figures are shown for illustrative purpose only. For instance, their sizes and shapes are not drawn to scale. It should be further noted that subscript i in this specification may assume any integer value between 1 and N.

[0030] In the optical spectral power monitoring apparatus 100 of FIG. 1A, the diffraction grating 120, by way of example, may be oriented such that the focused spots of the spectral channels fall onto the micromirrors 140 in a horizontal array. Depicted in FIG. 1B is a schematic front view of the micromirrors 140 shown in the embodiment of FIG. 1A. As a way of example, the micromirrors 140 may be arranged in a one-dimensional array along the x-direction (i.e., the horizontal direction in the figure), so as to receive the focused spots of the spatially separated spectral channels in a one-to-one correspondence. (As in the case of FIG. 1A, only three spectral channels are illustrated, each represented by a converging beam.) The reflective surface of each micromirror may lie in the x-y plane as defined in the figure and be movable, e.g., pivotable (or deflectable) about a horizontal axis such as the x-axis. Each spectral channel, upon reflection, may be deflected in the y-direction (e.g., downward) relative to its incident direction, so as to be directed into the output port 110-2 in FIG. 1A.

[0031] In FIG. 1B, the micromirrors 140 are shown to be under control of a set of mirror-control signals, e.g., voltage signals U_1 through U_N. By way of example, dashed box 170 in FIG. 1B illustrates a schematic side view of the micromirror 140-i, wherein the micromirror is shown to be subject to a mirror-control signal U_i, and consequently pivoting about the x-axis (pointing out of the plane of paper) at a pivoting angle θ_i. Each micromirror may have a quadratic response to its voltage control signal. For instance, the pivoting angle θ_i of the micromirror 140-i may be proportional to U_i^2. FIG. 1C shows an exemplary plot of θ_i as a function of U_i, where for the sake of convenience, θ_i is plotted along a horizontal axis,

whereas U_i is plotted along a vertical axis. The ensuing description considers a situation where for each micromirror (e.g., the micromirror **140-i**), only the pivoting motion in the positive angular range (i.e., $\theta_i > 0$) may be utilized. The general principles of the present invention, however, are not limited to this example; and in other alternative embodiments,

5 any angular ranges may be used.

[0032]   Also shown in FIG. **1C** is an exemplary plot of coupling efficiency $\eta_i(\theta_i)$ of the spectral channel λ_i into the output port **110-2** as a function of the pivoting angle θ_i of the corresponding micromirror **140-i**. As used herein, the coupling efficiency for a spectral channel is defined as the ratio of the amount of optical power coupled to the fiber core (e.g.,

10 of a single-mode optical fiber) in the fiber collimator serving as the output port **110-2** to the total amount of optical power incident upon the entrance surface of the fiber. A notable feature of the coupling efficiency curve in FIG. **1C** is that $\eta_i(\theta_i)$ displays a maximum value at a particular pivoting angle, e.g., θ_{io}, as shown in the figure. The value of θ_{io} is generally intrinsic to the configuration of the system. In the event that the micromirrors **140** are

15 configured to be parallel to each other in the absence of any control signal, θ_{io} may be substantially the same for all the spectral channels coupled into an output port (e.g., the output port **110-2** in FIG. **1A**). It should be appreciated that the general shape of the coupling efficiency curve shown in FIG. **1C** is characteristic of the coupling efficiency of any spectral channel under consideration.

20 [0033]   Referring back to FIGS. **1A** and **1B**. The micromirrors **140** may be configured such that each micromirror, at a nominal position, directs the corresponding spectral channel into the output port **110-2** at the maximum coupling efficiency. For instance, the nominal position for the micromirror **140-i** may correspond to the pivoting angle $\theta_i = \theta_{io}$. This nominal position may be established by a dc component U_{io} in the mirror-control signal U_i

25 applied to the micromirror **140-i**. As shown in FIG. **1C**, the mirror-control signal U_i may further contain an alternating (or "dither") component $\Delta U_i(t)$, for causing the micromirror **140-i** to pivot (or oscillate) about its nominal position. By way of example, let $\Delta U_i(t)$ be a

sinusoidal function of time, and the mirror-control signal U_i for the micromirror **140-i** accordingly be of the form,

$$U_i = U_{io} + \Delta U_i(t) = U_{io} + \Delta U_i \cos(\omega_i t) \tag{1}$$

where ΔU_i and ω_i are the dither-amplitude and dither-angular-frequency of the dither

5   component $\Delta U_i(t)$, respectively. Accordingly, the pivoting angle θ_i of the micromirror **140-i** may be given by

$$\theta_i(t) = \alpha U_i^2 = \theta_{io} + \theta_{i1} \cos(\omega_i t) + \theta_{i2} \cos(2\omega_i t) + \frac{1}{2}\alpha(\Delta U_i)^2 \tag{2}$$

where α is a proportionality constant, $\theta_{io} = \alpha U_{io}^2$ (also shown in FIG. **1C**), $\theta_{i1} = 2\alpha \Delta U_i U_{io}$,

and $\theta_{i2} = \frac{1}{2}\alpha(\Delta U_i)^2$. For small dither-amplitude, i.e., $\Delta U_i \ll U_{io}$, the terms in Eq. (2) that

10   have a quadratic dependence on ΔU_i may be neglected. Eq. (2) thus reduces to

$$\theta_i(t) = \theta_{io} + \theta_{i1} \cos(\omega_i t) \tag{3}$$

indicating that the micromirror has a nearly linear response to the dither component in its mirror-control signal. As a way of example to succinctly elucidate the principles of the present invention, the following discussion pertains to a situation where the micromirrors

15   each operate in the linear manner as described by Eq. (3). The results thus obtained, along with the general principles of the present invention, are applicable to the more general case of Eq. (2), nonetheless.

[0034]   The optical power level of the spectral channel λ_i coupled into the output port **110-2** is proportional to the coupling efficiency depicted in FIG. **1C**. Hence, as the pivoting

20   angle θ_i of the micromirror **140-i** varies (e.g., in a manner as shown in Eq. (2) or (3)), the optical power level of the spectral channel λ_i coupled into the output port **110-2** undergoes periodic oscillations, termed the "dither modulation signal," herein. The variation of the pivoting angle θ_i as a function of time t may be expressed as

$$\theta_i(t) = \theta_{io} + \Delta\theta_i(t) \tag{4}$$

where $\Delta \theta_i(t) = \theta_{i1} \cos(\omega_i t)$, in view of Eq. (3) above. If $P_i(\theta_i(t))$ represents the optical power level of the spectral channel λ_i coupled into the output **110-2**, expanding $P_i(\theta_i(t))$ about $\theta_i = \theta_{io}$ yields:

$$P_i(\theta_i(t)) = P_i(\theta_{io}) + \left.\frac{\partial P_i}{\partial \theta_i}\right|_{\theta_{io}} \Delta \theta_i + \left.\frac{\partial^2 P_i}{\partial^2 \theta_i}\right|_{\theta_{io}} (\Delta \theta_i)^2 + \ldots\ldots$$

$$= P_i(\theta_{io}) + [P_{i1}(\theta_{io})\theta_{i1}] \cos(\omega_i t) + [\frac{1}{2}P_{i2}(\theta_{io})\theta_{i1}^2] \cos(2\omega_i t) + \ldots \quad (5)$$

5   where $P_{i1}(\theta_{io}) = \left.\dfrac{\partial P_i}{\partial \theta_i}\right|_{\theta_{io}}$ and $P_{i2}(\theta_{io}) = \left.\dfrac{\partial^2 P_i}{\partial^2 \theta_i}\right|_{\theta_{io}}$, that is, the first-order and second-order

derivatives of $P_i(\theta_i(t))$ at $\theta_i = \theta_{io}$, respectively. The optical detector **150** may further convert the optical power levels of the received spectral channels to a consolidated electrical signal, e.g., a consolidated voltage signal that is a superposition of voltage components resulting from the received optical power levels respectively. By way of example, the voltage

10   component $V_i(\theta_i(t))$ originating from $P_i(\theta_i(t))$ of the spectral channels λ_i may be expressed as

$$V_i(\theta_i(t)) = V_{io}(\theta_{io}) + V_{i1}(\theta_{io}) \cos(\omega_i t) + V_{i2}(\theta_{io}) \cos(2\omega_i t) + \ldots\ldots \quad (6)$$

If the frequency response of the optical detector **150** is sufficiently uniform, it follows that

$$V_{i1}(\theta_{io}) = \beta[P_{i1}(\theta_{io})\theta_{i1}]$$
$$V_{i2}(\theta_{io}) = \beta[\frac{1}{2}P_{i2}(\theta_{io})\theta_{i1}^2] \quad (7)$$

15   where β is a predetermined constant, dependent upon the characteristics of the optical detector. The synchronous detection unit **160**, in communication with the optical detector **150**, may be set to detect one or more harmonic components (e.g., the terms associated with $\cos(\omega_i t)$ and $\cos(2\omega_i t)$) in Eq. (6) for each spectral channel.

[0035]   Those skilled in the art will recognize that $P_{i1}(\theta_{io})$ and $P_{i2}(\theta_{io})$ described above

20   are proportional to the first-order and second-order derivatives of the coupling efficiency $\eta_i(\theta_i)$ at $\theta_i = \theta_{io}$, respectively. As FIG. **1C** indicates, at $\theta_i = \theta_{io}$, $\eta_i(\theta_i)$ is maximum, therefore its first-order derivative is zero and second-order derivative is at a minimum value at $\theta_i = \theta_{io}$. It follows that $P_{i1}(\theta_{io}) = 0$, hence $V_{i1}(\theta_{io}) = 0$, and $V_{i2}(\theta_{io}) = \beta[\frac{1}{2}P_{i2}(\theta_{io})\theta_{i1}^2]$. As

such, the synchronous detection unit **160** may be set to detect the amplitudes of both the first and second harmonic components (e.g., $V_{i1}(\theta_{io})$ and $V_{i2}(\theta_{io})$) in Eq.(6), and the measurement of the first harmonic component (e.g., $V_{i1}(\theta_{io})$) may be used as a sensitive indicator of whether the nominal position of the micromirror is set at $\theta_i = \theta_{io}$.

5   **[0036]**   To relate the measurements provided by the synchronous detection unit **160** to the optical power levels of the spectral channels in the input multi-wavelength optical signal, a calibration may be performed. In this process, calibration optical signals, characterized by substantially the same (center) wavelengths λ_1 through λ_N as the spectral channels to be detected and having known input power levels P_1^{calib} through P_N^{calib}, may be coupled into the

10   input port **110-1**. (The calibration optical signals may be provided by a tunable laser, for instance.) The calibration optical signals subsequently impinge onto the micromirrors **140** by way of the diffraction grating **120** and the focusing lens **130**. The micromirrors **140**, being controlled by the respective mirror-control signals each as shown in Eq.(1), direct the calibration optical signals into the output port **110-2**. The optical detector **150** converts the

15   received calibration optical signals to a consolidated calibration voltage signal, which is then fed to the synchronous unit **160**. For example, the calibration optical signal λ_i may have an input power level P_i^{calib}. The synchronous unit **160** detects the amplitudes of the first and second harmonic components (e.g., $V_{i1}^{calib}(\theta_{io})$ and $V_{i2}^{calib}(\theta_{io})$) in Eq. (6). In the event that the detected amplitude of the first harmonic component (e.g., $V_{i1}^{calib}(\theta_{io})$) is not zero,

20   indicating that the nominal position of the micromirror **140-i** may not be set at θ_{io}, the dc component U_{io} in Eq. (1) may be adjusted until the amplitude of the first harmonic component in Eq. (6) becomes zero (i.e., $V_{i1}^{calib}(\theta_{io}) = 0$), thereby ensuring that the nominal position of the micromirror **140-i** is indeed maintained at the prescribed position θ_{io}. The amplitude of the second harmonic component thus detected, $V_{i2}^{calib}(\theta_{io})$, is recorded. A

25   calibration table, containing P_i^{calib} versus $V_{i2}^{calib}(\theta_{io})$ for all the calibration optical signals involved, may then be constructed and stored in the system (e.g., within the synchronous detection unit **160**).

[0037] · Subsequently in the course of operation, the input multi-wavelength optical signal emerges from the input port **110-1**, and the constituent spectral channels traverse substantially the same optical paths as the corresponding calibration optical signals during the calibration, while the micromirrors **140** are being controlled by the same set of the

5 mirror-control signals as during the calibration. Accordingly, the synchronous detection unit **160** measures the amplitudes of the first and second harmonic components (e.g., $V_{i1}(\theta_{io})$ and $V_{i2}(\theta_{io})$) in Eq. (6) for each spectral channel. Upon ensuring that $V_{i1}(\theta_{io}) = 0$, $V_{i2}(\theta_{io})$ is recorded. As a result, the optical power level P_i of the spectral channel λ_i in the input multi-wavelength optical signal may be given by:

10
$$P_i = \frac{V_{i2}(\theta_{io})}{V_{i2}^{calib}(\theta_{io})} P_i^{calib} \qquad (8)$$

In the event that the input multi-wavelength optical signal occupies a frequency range that is substantially higher than the frequency range designated for the dither modulation signals, Eq. (8) yields a time-averaged optical power level of the spectral channel λ_i in the input multi-wavelength optical signal. Conversely, if the input multi-wavelength optical signal is

15 allocated in a frequency range that is substantially lower than the frequency range designated for the dither modulation signals, Eq. (8) effectively provides a "real-time" monitoring (or tracking) of the optical power level of the spectral channel λ_i in the input multi-wavelength optical signal.

[0038] The synchronous detection unit **160** of FIG. **1A** may include a signal processor

20 designated for storing the aforementioned calibration table and deriving the optical power level of the respective spectral channels by use of Eq. (8), thereby providing an optical power spectrum (i.e., optical power level as a function of wavelength) of the input multi-wavelength optical signal. Those skilled in the art will appreciate that the above discussion, including Eqs. (1) through (8), applies to all the spectral channels of interest (i.e., the spectral channel

25 λ_i is merely used as an example in the above). Further, the result of Eq. (8), along with the aforementioned calibration procedure, is also applicable to a more general case where a micromirror's pivoting angle is described by Eq. (2) above.

[0039] It should be noted that by performing the aforementioned calibration, the details of the coupling efficiency curve for each spectral channel need not be known explicitly. The thus-described calibration also takes into account any systematic effect that may exist on a channel-by-channel (or wavelength-by-wavelength) basis, such as any optical loss a spectral channel may incur upon traversing from the input port 110-1 to the output port 110-2, without the need to measure such systematic effect separately. Furthermore, because the aforementioned calibration is performed on a channel-by-channel basis, the micromirrors 140 need not be configured and/or operated under identical conditions.

[0040] As such, a unique feature of the aforementioned embodiment of the present invention is that each micromirror, in conjunction with the output port 110-2, effectively functions as a "spatial light modulator." That is, each micromirror may be operated such to cause misalignment in coupling the corresponding spectral channel to the output port 110-2, which in turn gives rise to change in the optical power level of the spectral channel coupled into the output port 110-2, hence the dither modulation signal. By way of example, the output port 110-2 in FIG. 1A is shown to be in the form of a fiber collimator. It may alternatively be an aperture, or any other spatial filter known in the art that provides a spatial filtering of (or constriction to) the spectral channels reflected by the micromirrors. The micromirrors 140 above may be silicon micromachined mirrors, reflective ribbons (or membranes), or other types of beam-deflecting means known in the art. And each micromirror may be pivotable about at least one axis. What is important is that the micromirrors be individually controllable, so as to provide for the desired dither modulation signals. The underlying fabrication techniques for micromachined mirrors and associated actuation mechanisms are well documented in the art, see U.S. Patent No. 5,629,790 for example, which is fully and completely incorporated by reference.

[0041] In the present invention, the term "dither modulation signal" generally refers to any modulation in the optical power level of a spectral channel that is caused by the corresponding beam-modulating element, in contrast with other "intrinsic" modulation signals the input multi-wavelength optical signal may carry. (For example, in optical networking applications, the spectral channels in the input multi-wavelength optical signal

may each be modulated with a unique information signal.) Moreover, the dither modulation signals should be allocated in a spectral range that is sufficiently separated from the frequencies of other "intrinsic" modulation signals the spectral channels may carry.

[0042]   The optical spectral monitoring apparatus **100** thus is capable of introducing distinct dither modulation signals in multiple spectral channels in a frequency-division-multiplexed fashion. The distinct dither modulation signals enable the multiplexed spectral channels to be individually detected (e.g., by way of synchronous detection), whereby an optical power spectrum of the spectral channels can be derived. Such dither modulation signals may also be used as "identification markers" (or frequency tags) for identifying individual spectral channels in an optical networking application.

[0043]   One skilled in the art will recognize that in the above embodiments, the nominal position of a micromirror (e.g., the micromirror **140-i**) need not necessarily correspond with the maximum value in the coupling efficiency of the corresponding spectral channel (e.g., the spectral channel λ_i). For instance, the nominal position of the micromirror **140-i** may be set at a pivoting angle at which the coupling efficiency of the spectral channel λ_i is situated on either side of the maximum value shown in FIG. **1C**, if so desired in a practical application. In such a case, one of the harmonic components (e.g., the second harmonic component) in Eq. (6) may be used for determining the optical power level (in a manner similar to that described in Eq. (8)), whereas another harmonic component (e.g., the first harmonic component) in Eq. (6) may be used for ensuring the corresponding micromirror is maintained at the desired nominal position (or vice versa).

[0044]   In the aforementioned embodiment, the synchronous detection unit **160** generally comprises electrical circuits and signal processing algorithms devised for performing synchronous detection of the dither modulation signals in the optical power levels of the spectral channels. For instance, it may employ multiple processors each designated to a particular dither modulation signal. It may also comprise a lock-in detector operated in a time-division-multiplexed sequence. From the teachings of the present invention, those skilled in the art will recognize that the dither components in the mirror-control signals

applied to the micormirrors may be of other functional forms (in addition to the sinusoidal function of time as exemplified in Eq. (1) above), so long as the dither modulation signals thus produced in the optical power levels of the spectral channels contain mutually orthogonal components and the corresponding dither frequencies are allocated in a spectral

5 range that is sufficiently separated from the frequencies of other "intrinsic" modulation signals the spectral channels may carry.

[0045] The general principles of the present invention may also be applicable to a situation where it may be desired for the dither components in two (or more) mirror-control signals to share the same dither frequency. Consider the embodiment of FIG. **1B** as a way of

10 example. Assume that $\omega_1 = \omega_i$ for the micrmirrors **140-1, 140-i**, $\omega_2 = \omega_j$ for the micrmirrors **140-2, 140-j**, and $\omega_3 = \omega_k$ for the micrmirrors **140-3, 140-k**, where the dither-angular-frequencies ω_1, ω_2, ω_3 are mutually distinct (e.g., $\omega_1 \neq \omega_2 \neq \omega_3$), and the remaining dither-angular-frequencies are likewise mutually distinct. In such a scenario, the dither modulation signals in the optical power levels of the spectral channels λ_1, λ_i no longer contain mutually

15 orthogonal components, thus becoming "non-distinct". Likewise, the dither modulation signals associated with the spectral channels λ_2, λ_j, or those associated with the spectral channels λ_3, λ_k, are also "non-distinct". FIG. **2** depicts a second embodiment of an optical spectral power monitoring apparatus of the present invention, pertaining to this situation. By way of example, optical spectral power monitoring apparatus **200** makes use of the general

20 architecture along with a number of the elements used in the embodiment of FIG. **1A**, as indicated by those elements labeled with identical numerals. This embodiment implements an array of input and output ports **210**, including an input port **210-1** and a plurality of output ports **210-2** through **210-M** (M ≥ 3). As in the embodiment of FIG. **1A**, each output port serves as a spatial filter, and is shown in the form of a fiber collimator by way of example.

25 The micromirrors **140** may be operated such that the spectral channels λ_1, λ_2, λ_3 (carrying dither modulation signals characterized by the dither-angular-frequencies ω_1, ω_2, ω_3) are coupled into a second output port **210-3**, whereas the remaining spectral channels are coupled into a first output port **210-2** (or vice versa). This ensures that the optical power levels coupled into each output port carry distinct dither modulation signals. First and second

optical detectors **252**, **253** may be optically coupled to the first and second output ports **210-2**, **210-3**, respectively. First and second synchronous detection units **262**, **263** may in turn be in communication the first and second optical detectors **252**, **253**, respectively. The detection of the dither modulation signals in each output port may be carried out in a manner

5   substantially similar to that described with respect to FIG. **1A**. First and second calibration processes may also be performed respectively with respect to the measurements provided by the first and second synchronous detection units **262**, **263**, in a manner substantially similar to that described above, so as to yield an optical power spectrum of the input multi-wavelength optical signal.

10   **[0046]**   In the present invention, the dither components in the mirror-control signals may generally be classified into distinct "dither groups", wherein each dither group contains one or more dither components that are mutually orthogonal (e.g., the dither components may be characterized by sinusoidal functions of time with distinct frequencies, as exemplified above). The dither components in different dither groups need not necessarily be orthogonal.

15   (e.g., two dither components belonging to two dither groups may be characterized by sinusoidal functions of time with the same frequency). Accordingly, the number of the output ports implemented in an optical spectral power monitoring apparatus of the present invention should be commensurate with the number of the distinct dither groups devised for a given application, so as to ensure that the spectral channels coupled into each output port

20   carry distinct dither modulation signals.

[0047]   It is known that the diffraction efficiency of a diffraction grating may be polarization-dependent. For instance, the diffraction efficiency of a grating in a standard mounting configuration may be higher for p (or TM) polarization that is perpendicular to the groove lines on the grating than for s (or TE) polarization that is orthogonal to p-polarization,

25   or vice versa. Such polarization-sensitive effects may become appreciable for a grating with a large number of groove lines (per unit length). In applications where such polarization-sensitive effects are deemed undesirable, a polarization diversity scheme may be implemented in the present invention. FIGS. **3A-3C** depict third and fourth embodiments of

an optical spectral power monitoring apparatus of the present invention, each employing an array of micromirrors as the beam-modulating elements in a polarization diversity scheme.

[0048]   FIG. 3A is a schematic top view of a third embodiment of an optical spectral power monitoring apparatus of the present invention. By way of example, optical spectral

5   power monitoring apparatus **300A** may make use of the general architecture as well as a number of the elements used in the embodiment of FIG. 1A, as indicated by those elements labeled with identical numerals. In this case, a polarization-separating element **381** may be disposed along the optical path between the input port **110-1** and the diffraction grating **120**, and serves to decompose the input multi-wavelength optical signal into a p-polarization

10   component and an s-polarization component (or first and second polarization components). As a way of example, assuming that p-polarization is the preferred direction of the diffraction grating **120** (i.e., the diffraction efficiency is higher for p-polarization than for s-polarization), the s-polarization component may then be rotated by approximately 90-degrees by a polarization-rotating element **391**, whereby the optical signals incident onto the

15   diffraction grating **120** all possess p-polarization. It should be appreciated that while the polarization-rotating element will attempt rotate the s-polarization component by precisely 90-degrees, certain variations may be present in practice and will not significantly affect the overall performance of the invention. The diffraction grating **120** subsequently separates the incident optical signals by wavelength respectively into first and second sets of optical beams

20   (wherein each group may contain optical beams with wavelengths λ_1 through λ_N, for instance). The focusing lens **130** may focus the first and second optical beams associated with the same wavelength (e.g., λ_i) onto the same micromirror (e.g., the micromirror **140-i** in FIG. **1B**).

[0049]   FIG. **3B** depicts a schematic side view of how the optical beams may traverse the

25   optical spectral power monitoring apparatus **300A**, where the incoming and reflected optical beams are shown in solid and dashed lines, respectively, for purpose of illustration. Upon being reflected by the respective micromirrors **140**, the diffraction grating **120** multiplexes the reflected first and second sets of optical beams into first and second "returning" polarization components (corresponding to the original p-polarization and s-polarization

components), respectively. An auxiliary polarization-rotating element **392** may rotate the polarization one of the returning polarization components (e.g., the first returning polarization component) by 90-degrees, such that the first and second returning polarization components are re-combined by way of traversing a polarization-combining element **382** 5 (wherein the two constituent polarization components associated with each wavelength re-combine to form a single spectral channel), prior to being coupled into the output port **110-2**.

[0050] In the embodiment of FIGS. **3A-3B**, the micromirrors **140** may operate under a set of mirror-control signals similar to that described with respect to FIG. **1A**. Accordingly, the optical power levels coupled into the output port **110-2** may carry the same characteristic 10 dither modulation signals as described above. The detection of the dither modulation signals by way of the synchronous detection unit **160** in conjunction with the optical detector **150**, and the determination of the optical power spectrum of the input multi-wavelength optical signal thus ensued, may be carried out in a manner substantially similar to that described with respect to FIG. **1A**.

[0051] The embodiment of FIGS. **3A-3B** may be further modified to provide an optical 15 power spectrum for each polarization component in the input multi-wavelength optical signal, as illustrated in FIG. **3C**. FIG. **3C** is a schematic top view of a fourth embodiment of an optical spectral power monitoring apparatus of the present invention. By way of example, optical spectral power monitoring apparatus **300B** may be built upon the embodiment of 20 FIGS. **3A-3B**, as indicated by the elements labeled with identical numerals. In this case, the second and first returning polarization components from the diffraction grating **120** may be coupled into the output port **110-2** (underneath the input port **110-1** in this schematic top view) and an auxiliary output port **110-3**, respectively. This ensures that the optical power levels coupled into each output port carry distinct dither modulation signals. An auxiliary 25 optical detector **151**, along with an auxiliary synchronous detection unit **161**, may be in communication with the auxiliary output port **110-3**. The detection of the dither modulation signals in each output port may be carried out in a manner substantially similar to that described with respect to FIG. **1A**. Furthermore, first and second calibration processes may be performed respectively with respect to the measurements provided by the synchronous

detection units **160, 161**, in a manner substantially similar to that described in FIG. **1A**. As such, an optical power spectrum associated with each polarization component in the input multi-wavelength optical signal can be independently obtained in the embodiment of FIG. **3C**. ·

5   **[0052]** ·   The beam-modulating elements in the present invention may be alternatively provided by other types of spatial light modulators known in the art. By way of example, FIG. **4A** shows a schematic top view of a fifth embodiment of an optical spectral power monitoring apparatus according to the present invention, employing an array of electro-optic modulating elements **440** in a polarization diversity scheme. Optical spectral power

10   monitoring apparatus **400** may make use of the general architecture along with some of the elements employed in the embodiment of FIG. **3C**, as indicated by those elements labeled with identical numerals. In this case, the polarization-separating element **381** may decompose the input multi-wavelength optical signal from the input port **110-1** into a p-polarization component and an s-polarization component (or first and second polarization

15   components). In the event that p-polarization is the preferred direction of the diffraction grating **120** (i.e., the diffraction efficiency is higher for p-polarization than for s-polarization), the polarization-rotating element **391** may rotate the polarization of the s-polarization component (or the second polarization component) by 90-degrees. The diffraction grating **120** subsequently separates the incident optical signals by wavelength

20   respectively into first and second sets of optical beams (wherein each set contains optical beams with wavelengths λ_1 through λ_N, for instance). The focusing lens **130** may focus the diffracted optical beams onto an array of beam-modulating elements **440** which may comprise electro-optic intensity modulating elements and which may be followed by a beam-reflector **470** (e.g., a mirror). The first and second optical beams associated with the same

25   wavelength (e.g., λ_i) may impinge on the same modulating element.

[0053]   The electro-optic modulating elements **440** may operate under control of a set of distinct alternating (or dither) control signals, which in one form may be sinusoidal functions of time at a set of distinct frequencies. Each modulating element may be configured such to introduce a dither modulation signal in the optical power level of a corresponding optical

beam that includes a substantially linear response to the control signal to which it is subject. As such, upon a round-trip through the respective electro-optic modulating elements **440** by way of the beam-reflector **470**, and further multiplexed by the diffraction grating **120**, the first and second sets of optical beams may be directed into first and second optical detectors 5 **451**, **452** respectively, such that the optical power levels received by the respective first and second optical detectors **451**, **452** carry distinct dither modulation signals. In FIG. **4A** and FIG. **4B** as follows, the incoming and reflected optical beams are shown in solid and dashed lines, respectively, for purpose of illustration.

[0054] FIG. **4B** shows a schematic side view of how the optical beams traverse the 10 optical spectral power monitoring apparatus **400**. By way of example, only the first polarization component of the input multi-wavelength optical signal and subsequently the first set of optical beams are explicitly shown. A first synchronous detection unit **461**, in communication with the first optical detector **451**, serves to detect the dither modulation signals associated with the first set of optical beams. Likewise, a second synchronous 15 detection unit **462** (see FIG. **4A**) may be in communication with the second optical detector **452** (see FIG. **4A**), for detecting the dither modulation signals associated with the second set of optical beams. As in the case of FIG. **3C**, first and second calibration processes may be performed respectively with respect to the measurements provided by the first and second synchronous detection units **461**, **462**, such that an optical power spectrum associated with 20 each polarization component in the input multi-wavelength optical signal can be independently determined.

[0055] In the embodiment of FIGS. **4A-4B**, the first and second sets of optical beams, upon being multiplexed by the diffraction grating **120**, may also be coupled into first and second output ports (e.g., in a manner as depicted in FIG. **3C**), if so desired in a practical 25 application. The first and second output ports may in turn be coupled to first and second optical detectors, which are in communication with first and second synchronous units, respectively. Alternatively, the first and second sets of optical beams, upon being multiplexed by the diffraction grating **120**, may be re-combined (e.g., in a manner as depicted in FIGS. **3A-3B**), prior to be directed into an optical detector (or an output port).

[0056]   In the present invention, an electro-optic modulating element may be a liquid crystal based intensity modulator known in the art, or any other electro-optic intensity modulator known in the art, capable of modulating the optical power level of an optical beam in such a way that the modulation thus produced includes a substantially linear response to the control signal applied to the modulating element. The polarization-separating element **381** may be a polarization beam splitter, a birefringent beam displacer, or other types of polarization-separating means known in the art. The polarization-rotating element **391**, or the auxiliary polarization-rotating element **392**, may be a half-wave plate, a Faraday rotator, a liquid crystal rotator, or any other polarization-rotating means known in the art that is capable of rotating the polarization of an optical beam by 90-degrees. The polarization-combining element **382** may be a birefringent element, e.g., a birefringent beam displacer operated in reverse. It may also be other means known in the art that is capable of combining two optical beams by way of polarization.

[0057]   Moreover, the wavelength-disperser in the present invention may generally be a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a transmission grating, a dispersing prism, or other types of wavelength-separating means known in the art. The beam-focuser may generally be an assembly of one or more focusing lenses, or other types of beam-focusing means known in the art. The focusing function may also be accomplished by using a curved diffraction grating that performs a dual function of wavelength-separating and beam-focusing. The input port may be a fiber collimator, e.g., in the form of a collimating lens (such as a GRIN lens) and a ferrule-mounted fiber packaged together in a mechanically rigid stainless steel (or glass) tube. For the ease of alignment, the fiber collimators serving as the input and output ports in any of the above embodiments may be conveniently mounted along a V-groove fabricated on a substrate made of silicon, plastic, or ceramic, as commonly practiced in the art. The optical detector may be a PN photo detector, a PIN photo detector, an avalanche photo detector (APD), or other types of optical power sensing means known in the art. As will be appreciated from the teachings of this specification, one skilled in the art will know how to design a suitable optical spectral power monitoring apparatus according to the present invention, for a given application.

[0058]   To ensure the requisite alignment between the spectral channels and the respective beam-modulating elements (i.e., the micromirrors 140 in FIG. 1A or the electro-optic modulating elements 440 in FIG. 4A), an optical spectral power monitoring apparatus of the present invention may make use of one or more reference signals and corresponding reference-position-sensing elements, along with appropriate alignment-adjusting elements, to monitor the alignment between the spectral channels and the underlying beam-modulating elements and to correct for shift in the alignment that may occur over the course of operation. FIG. 5 depicts a schematic top view of a sixth embodiment of an optical spectral power monitoring apparatus of the present invention. By way of example to illustrate the general principles of the present invention, optical spectral power monitoring apparatus 500 may make use of the general architecture along with a number of the elements used in the embodiment of FIG. 1A, as indicated by those elements labeled with identical numerals. The following description will use this system as an example to illustrate how best to ascertain and further maintain the requisite alignment between the spectral channels and the underlying beam-modulating elements. The operation of the embodiment of FIG. 5 as an optical spectral power monitoring device may be substantially as described in any one of the above embodiments. (Hence, some of the elements depicted in the aforementioned embodiments, such as the output port(s) and/or optical detector(s), are not explicitly shown in FIG. 5.)

[0059]   In the optical spectral power monitoring apparatus 500, the input port 110-1 transmits a multi-wavelength optical signal containing wavelengths λ_1 through λ_N along with a reference signal containing wavelength λ_c. The diffraction grating 120 angularly separates the incident multi-wavelength optical signal along with the reference signal by wavelength into multiple spectral channels λ_1 through λ_N and a reference spectral component λ_c having a predetermined relative arrangement. The focusing lens 130 may focus the reference spectral component and the spectral channels into corresponding focused spots, e.g., in a predetermined spatial array (termed "spectral array" herein) with the predetermined relative arrangement. An optical-element array 540, including a reference-position-sensing element 540-C and a plurality of beam-modulating elements 540-1 through 540-N (e.g., the micromirrors 140 in FIG. 1A), may be positioned such that when the reference spectral component λ_c impinges onto the reference-position-sensing element 540-C at a

predetermined location x_0, the spectral channels λ_1 through λ_N impinge onto the beam-modulating elements **540-1** through **540-N** at designated locations x_1 through x_N. This provides a simple and effective way to align the spectral channels with the respective beam-modulating elements. The optical-element array **540** may be integrated into a single

5 structure, e.g., by mounting and/or fabricating the constituent optical elements on a substrate. It should be appreciated that the focused spots of the diffracted optical beams impinging onto the optical-element array **540** may be unevenly spaced.

[0060] The optical spectral monitoring apparatus **500** of FIG. **5** may further comprise an alignment-adjusting element **560-1** which in one form may be an actuation device coupled to

10 the optical-element array **540**, for causing the optical-element array **540** as a whole – therefore the reference-position-sensing element **540-C** and the beam-modulating elements **540-1** through **540-N** in tandem - to move, e.g., translate and/or rotate, thereby adjusting a relative alignment between the spectral array formed by the diffracted optical beams and the underlying optical-element array. The optical spectral power monitoring apparatus **500** of

15 FIG. **5** may additionally include a processing element **560-2**, for monitoring the real-time impinging position of the reference spectral component λ_c on the reference-position-sensing element **540-C** and for controlling the actuation device **560-1** accordingly, so as to ensure that the reference spectral component λ_c stays aligned at the predetermined location x_0 and therefore the spectral channels λ_1 through λ_N stay aligned at the designated locations x_1

20 through x_N. The thus-described alignment-monitoring-adjusting process may be carried out periodically, or continuously by way of servo-control. (In the latter scenario, the actuation device **560-1** and the processing element **560-2** constitute a servo-control unit **560**.) As such, the optical spectral power monitoring apparatus **500** is capable of actively correcting for shift in the alignment that may occur over the course of operation (e.g., due to environmental

25 effects such as thermal and/or mechanical disturbances), and therefore is more robust in performance.

[0061] In the embodiment of FIG. **5**, the reference-position-sensing element **540-C** may be a position sensitive detector, a quadrant detector, a split detector, or any other position-sensitive means known in the art, which allows the real-time impinging position (in one or

two dimensions) of an optical beam to be monitored by way of electrical (e.g., current or voltage) signals produced by the sensing element. Alternatively, it may comprise two "reference-beam-modulating elements", which may be substantially similar to the beam-modulating elements employed in the system in configuration and operation. The reference-

5   beam-modulating elements may be operated such to introduce two distinct "reference dither modulation signals" in the optical power level of the corresponding reference spectral component λ_c. By detecting the reference dither modulation signals using an appropriate differential detection scheme known in the art, the impinging position of the reference spectral component λ_c can be deduced.

10   [0062]   Furthermore, the actuation device 560-1 may be a voice coil actuator, a stepping motor, a solenoid actuator, a piezoelectric actuator, or other types of actuation means known in the art. The processing element 560-2 may include electrical circuits, controllers and signal processing algorithms for processing the output signals received from the reference-position-sensing element 540-C and deriving from the detected signals the real-time

15   impinging position of the reference spectral component λ_c. The processing element 560-2 accordingly generates appropriate control signals to be applied to the actuation device 560-1.

[0063]   A skilled artisan will appreciate that instead of (or in conjunction with) of moving the optical-element array 540 relative to the spectral array as described above, the focusing lens 130 in FIG. 5 may be alternatively (or additionally) moved (e.g., translated or rotated),

20   thereby performing a similar alignment function. From the teachings of the present invention, those skilled in the art will further appreciate that one or more auxiliary reference signals and corresponding reference-position-sensing elements, along with suitable alignment-adjusting elements, may be additionally employed in an optical spectral power monitoring apparatus of the present invention to complement the aforementioned function of

25   the reference spectral component λ_c.

[0064]   In the present invention, one or more reference signals may generally be any optical signals with well-defined and stable center wavelengths that do not substantially coincide with any of the wavelengths of the spectral channels under consideration. By way

of example, the reference signal in FIG. 5 is shown to have a wavelength λ_c that is shorter (or longer) than any of the wavelengths of the spectral channels. In general, the spectral channels need not be evenly spaced in wavelength (or frequency).

[0065]   In the embodiment of FIG. 5, the multi-wavelength optical signal containing wavelengths λ_1 through λ_N may be provided by an input optical fiber **501** coupled to the fiber collimator that serves as the input port **110-1**. The reference signal λ_c may be provided by a reference light source **502**, which may be a distributed feedback (DFB) laser, a Fabry-Perot (FP) laser (in conjunction with an appropriate modulation/control system that serves to suppress the mode hopping and stabilizes the output signal), or any other light source known in the art that can provide an appropriate reference signal with well-defined and stable wavelength. An optical combiner **503** (e.g., a fiber-optic fused coupler) may be used to couple the reference light source **502** to the input optical fiber **501**, effective to direct both the multi-wavelength optical signal and the reference signal into the input port **110-1**. The optical spectral power monitoring apparatus **500** thus has an independent, internal reference light source. (In the event that one or more auxiliary reference signals are employed in the present invention, one or more auxiliary reference light sources may be coupled to the input fiber **501** by one or more auxiliary optical combiners in a similar manner; or a single reference light source capable of providing a plurality of distinct reference signals may be implemented, in lieu of the reference light source **502**.) Alternatively, the multi-wavelength optical signal itself may include one or more spectral components (e.g., one or more service channels in an optical network) that can serve as one or more reference signals, as in WDM optical networking applications. In such scenario, the internal reference light source **502** along with the optical combiner **503** need not be implemented.

[0066]   Those skilled in the art will recognize that the exemplary embodiments described above provide only a few of many optical spectral power monitoring systems that can be constructed according to the present invention. Various means and methods can be devised to perform the designated functions in an equivalent manner. Moreover, various changes, substitutions, and alternations can be made herein without departing from the principles and

the scope of the present invention. Accordingly, the scope of the present invention should be determined by the following claims and their legal equivalents.